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16. ABSTRACT

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CHARACTERIZING THE UNCERTAINTY OF PESTICIDE LEACHING IN AGRICULTURAL SOILS

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ABSTRACT

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A Monte-Carlo numerical simulation procedure for making regional assessments of pesticide leaching has been developed. This procedure uses probability density functions for organic matter, field capacity, and wilting point developed from information on approximately 3000 soils. Variations in climatic conditions were incorporated by random selection of yearly rainfall data. The procedure was demonstrated for aldicarb applied to corn grown in Ohio. A total of 2000 parameter sets were evaluated using the unsaturated zone model PRZM. The simulation results indicated that convergence of the 90th, 95th, and 99th percentiles for movement past 0.3, 0.6, 0.9, and 1.5 m was obtained after 500 simulations. The relative uncertainty associated with these percentiles was approximately 50% after 1500 simulations. The downward movement of aldicarb residues was most sensitive to changes in field capacity. These simulations, coupled with additional soil-specific simulations, indicated no significant movement of aldicarb residues beyond 1.8 m for applications to Ohio corn.

INTRODUCTION

The detection of a variety of pesticides in groundwater (Cohen et al., 1986) has resulted in an increase in research designed to better quantify pesticide movement and degradation. These studies have included the development of predictive models (e.g., Bonazountas and Wagner, 1981; Enfield et al., 1982; Carsel et al., 1984) for designing strategies for preventing or minimizing pesticide residues in groundwater and preventing their occurrence in drinking water.

The degradation and movement of pesticides in soil is a complex process affected by soil, climatic, agricultural, and pesticide characteristics. Spatial variations in soil characteristics and temporal variations in climatic

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conditions complicate the assessment of the leaching potential of a pesticide. Monte-Carlo techniques, however, can be used to account for the variability associated with key parameters if appropriate probability functions can be developed.

The purpose of this investigation was to develop a simple screening procedure for assessing pesticide leaching potential. Monte-Carlo techniques are used to generate soil parameters from probability density functions developed from national soil distributions. Cause and effect investigations were conducted for model parameter combinations identified as potentially sensitive. A future paper (Carsel et al., 1988) discusses more site specific techniques that include prediction of groundwater loadings.

The assessment procedure is demonstrated for applications of aldicarb to Ohio corn fields. The unsaturated zone model used in this study was the Pesticide Root Zone Model (PRZM) developed by Carsel et al. (1984, 1985). The suitability of PRZM for modeling movement and degradation of pesticides including aldicarb has been demonstrated using a wide range of field data (Carsel et al., 1985, 1986; Jones et al., 1986; Lorber and Offutt, 1986). Generally the model predictions of residue movement are conservative, i.e. predicted movement is slightly greater than actual movement (Jones et al., 1986; Lorber and Offutt, 1986). The assessment technique described in this paper could be adapted for use with other unsaturated zone models.

DEVELOPMENT OF PROBABILITY DENSITY FUNCTIONS FOR SOIL PROPERTIES

Any stochastic procedure for evaluating pesticide movement requires well-defined probability distributions for soil characteristics affecting solute movement. The unsaturated zone model used in these simulations (PRZM) requires values of bulk density, organic matter, field capacity, and wilting point as a function of depth. The distributions for these properties were identified using information on 2942 soil series in 40 states obtained from the U.S. Soil Conservation Service. These soil series were sorted by hydrological class and stratum. A total of 186, 1216, 870, and 670 soils were in A, B, C, and D classes, respectively. The strata used in this evaluation were 0 to 0.3, 0.3 to 0.6, 0.6 to 0.9, and 0.9 to 1.2 m.

Descriptive statistics for selected soil characteristics are reported in Tables 1–4. (Soil characteristics not required in this evaluation will be reported elsewhere.) The coefficient of variation is highest for organic matter, field capacity, and wilting point and lowest for bulk density. Organic matter, field capacity, and wilting point tend to increase across hydrologic class and decrease with depth within each class. These results are consistent with the definition of a soils hydrologic class (McCuen, 1982). The magnitude of the variation is similar for other hydraulic characteristics (Warrick and Nielsen, 1980; Sharma and Rogowski, 1985). Considerable variation in soil characteristics occurs between and within hydrological classes.

Distributions for the field capacity, wilting point, and organic matter were

TABLE 1

Descriptive statistics for bulk density ($Mg\,m^{-3}$)

Stratum (m)	Sample size	Mean	Median	25th–75th percentile	s.d.	C_{var} (%)
Class A						
0.0–0.3	40	1.45	1.53	1.4–1.6	0.24	16.2
0.3–0.6	44	1.50	1.56	1.4–1.7	0.23	15.6
0.6–0.9	38	1.57	1.55	1.5–1.7	0.16	10.5
0.9–1.2	34	1.58	1.59	1.5–1.7	0.13	8.4
Class B						
0.0–0.3	459	1.44	1.45	1.3–1.6	0.19	13.5
0.3–0.6	457	1.51	1.53	1.5–1.7	0.19	12.2
0.6–0.9	438	1.56	1.57	1.5–1.8	0.19	12.3
0.9–1.2	384	1.60	1.60	1.5–1.8	0.21	12.9
Class C						
0.0–0.3	398	1.46	1.48	1.4–1.6	0.22	15.0
0.3–0.6	395	1.58	1.59	1.5–1.7	0.23	14.5
0.6–0.9	371	1.64	1.65	1.5–1.8	0.23	14.2
0.9–1.2	326	1.67	1.68	1.5–1.8	0.23	14.0
Class D						
0.0–0.3	259	1.52	1.53	1.4–1.8	0.24	15.9
0.3–0.6	244	1.63	1.66	1.5–1.8	0.26	16.0
0.6–0.9	214	1.67	1.72	1.5–1.8	0.27	16.3
0.9–1.2	180	1.65	1.72	1.5–1.8	0.28	17.0

s.d. = standard deviation; C_{var} = coefficient of variation.

obtained by fitting members of the Pearson and Johnson transformation systems (Johnson and Kotz, 1970). The Kolmogorov–Smirnov test (Siegel, 1956; SAS, 1982) was used to select the transformation providing the best-fitting density. In nearly every case, approximations that best described the empirical distributions were obtained with the Johnson transformations. All of these transform an original random variable into one having a normal distribution. These models, as used here, are represented by:

Log Normal: $Y = \ln X$

Johnson s_U: $Y = \sinh^{-1}(X/X_{UB})$

Johnson s_B: $Y = \ln [X/(X_{UB} - X)]$

where ln = natural log; $\sinh^{-1}$ = hyperbolic arc sine; X = original variable; X_{UB} = upper bound on original variable (60% by volume for field capacity and wilting point, 11% for organic matter).

Tables 2–4 provide the mean values of appropriately transformed variables and the associated variation along with the Kolmogorov–Smirnov test statistics and the probability of obtaining a more extreme value.

TABLE 2

Descriptive statistics and distribution model for field capacity (percent by volume)

Stratum (m)	Sample size	Original data				Distribution model				
		Mean	Median	s.d.	C_{var} (%)	Transform.	Mean	s.d.	D^a	P^b
Class A										
0.0–0.3	52	11.8	9.4	9.2	78	ln	2.25	0.65	0.066	> 0.15
0.3–0.6	50	9.6	8.1	7.9	82	ln	1.99	0.73	0.964[c]	0.284
0.6–0.9	42	7.3	5.9	5.8	79	ln	1.73	0.73	0.976[c]	0.633
0.9–1.2	39	7.1	5.8	5.0	70	ln	1.73	0.71	0.972[c]	0.515
Class B										
0.0–0.3	459	19.5	19.1	8.3	42	s_U	0.316	0.13	0.037	0.129
0.3–0.6	454	18.8	18.8	7.4	39	s_U	0.311	0.12	0.025	> 0.15
0.6–0.9	435	18.7	18.7	7.1	39	s_U	0.298	0.11	0.039	0.105
0.9–1.2	373	17.5	17.5	7.6	43	s_U	0.288	0.12	0.037	> 0.15
Class C										
0.0–0.3	371	22.4	22.5	7.8	35	s_U	0.363	0.12	0.047	0.047
0.3–0.6	362	22.8	23.2	7.8	34	s_U	0.369	0.12	0.060	< 0.01
0.6–0.9	336	22.7	22.9	8.6	38	s_U	0.368	0.13	0.039	0.105
0.9–1.2	290	22.2	21.3	8.9	40	s_U	0.359	0.13	0.051	< 0.061
Class D										
0.0–0.3	230	24.1	24.2	9.1	38	s_U	0.387	0.14	0.056	0.079
0.3–0.6	208	26.1	26.3	9.3	36	s_U	0.419	0.14	0.043	> 0.15
0.6–0.9	178	25.0	25.6	8.2	33	s_U	0.403	0.13	0.042	> 0.15
0.9–1.2	146	24.1	24.4	8.1	33	s_U	0.390	0.12	0.045	> 0.15

s.d. = standard deviation; C_{var} = coefficient of variation.
[a] Kolmogorov–Smirnov test statistic.
[b] Probability of obtaining a more extreme value of D.
[c] Shapiro–Wilk test statistic (for sample sizes 50 or less).

Because the objective was to obtain reasonably good approximations of various distributions for later use in simulation, rigorously perfect fits were not considered absolutely necessary. These approximations are considered to be acceptable for simulation because they adequately described the general behavior of the data, and the variation between observed and predicted values would be indistinguishable within the accuracy of the simulations. By normalizing the variables, correlations among the simulated variables can be easily incorporated.

Approximations for bulk density were not developed because the coefficient of variation was less than 20% and because descriptive statistics (Table 1) indicated that 75% of the values fell within a narrow range for all soils and depths evaluated. Because the mean and median values were nearly identical and because measures of skewness were near zero, the median value was determined to adequately represent bulk density.

TABLE 3

Descriptive statistics and distribution model for wilting point (percent by volume)

Stratum (m)	Sample size	Original data				Distribution model				
		Mean	Median	s.d.	C_{var} (%)	Transform.	Mean	s.d.	D^a	P^b
Class A										
0.0–0.3	118	4.1	3.1	3.4	82	ln	1.83	0.64	0.110	< 0.01
0.3–0.6	119	3.2	2.3	2.4	75	ln	0.915	0.71	0.080	0.061
0.6–0.9	113	2.9	2.1	2.3	81	s_B	3.32	0.88	0.058	> 0.15
0.9–1.2	105	2.6	1.9	2.3	87	s_B	3.43	0.92	0.080	0.095
Class B										
0.0–0.3	880	9.0	8.7	4.0	45	s_U	0.150	0.066	0.059	< 0.01
0.3–0.6	883	9.4	9.3	4.3	46	s_U	0.156	0.071	0.031	0.039
0.6–0.9	866	9.1	8.9	4.4	48	s_U	0.151	0.072	0.038	< 0.01
0.9–1.2	866	8.6	8.4	4.6	53	s_U	0.143	0.076	0.047	< 0.01
Class C										
0.0–0.3	678	10.8	10.4	5.1	48	s_U	1.63	0.62	0.051	< 0.01
0.3–0.6	677	12.2	12.1	5.6	46	s_U	0.202	0.091	0.025	> 0.15
0.6–0.9	652	12.2	11.9	6.0	49	s_U	0.201	0.096	0.029	> 0.15
0.9–1.2	582	11.8	11.5	5.7	48	s_U	0.194	0.092	0.039	0.032
Class D										
0.0–0.3	495	14.6	13.8	7.6	52	s_U	1.26	0.76	0.050	< 0.01
0.3–0.6	485	16.9	17.0	7.3	43	s_U	0.277	0.12	0.045	< 0.01
0.6–0.9	437	16.6	16.3	7.4	45	s_U	0.271	0.12	0.040	0.081
0.9–1.2	401	15.7	15.1	7.6	48	s_U	0.257	0.12	0.033	> 0.15

s.d. = standard deviation; C_{var} = coefficient of variation.
[a] Kolmogorov–Smirnov test statistic.
[b] Probability of obtaining a more extreme value of D.

Field capacity, wilting point, and organic matter are correlated (Rawls et al.,1982). Pair-wise correlations determined from the soil data for field capacity, wilting point, and organic matter are shown in Table 5.

EXAMPLE ASSESSMENT

The Monte-Carlo procedure is demonstrated for applications of aldicarb to corn in Ohio. This case was chosen because of the availability of data from an earlier modeling study in the area (Donigian and Carsel, 1987). In this assessment, parameter sets for 2000 cases were generated and simulated using the unsaturated model PRZM. In this section, aldicarb residues will refer to aldicarb and its two carbamate metabolites aldicarb sulfoxide and aldicarb sulfone. Degradation will refer to the transformation of carbamates to non-carbamates.

TABLE 4

Descriptive statistics and distribution model for organic matter (percent by weight)

Stratum (m)	Sample size	Original data				Distribution model[a]			
		Mean	Median	s.d.	C_{var} (%)	Mean	s.d.	D^b	P^c
Class A									
0.0–0.3	162	0.86	0.62	0.79	92	−4.53	0.96	0.051	> 0.15
0.3–0.6	162	0.29	0.19	0.34	114	−5.72	0.91	0.044	> 0.15
0.6–0.9	151	0.15	0.10	0.14	94	−6.33	0.83	0.061	> 0.15
0.9–1.2	134	0.11	0.07	0.11	104	−6.72	0.87	0.090	< 0.01
Class B									
0.0–0.3	1135	1.3	1.1	0.87	68	−4.02	0.76	0.029	0.022
0.3–0.6	1120	0.50	0.40	0.40	83	−5.04	0.77	0.026	0.059
0.6–0.9	1090	0.27	0.22	0.23	84	−5.65	0.75	0.041	< 0.01
0.9–1.2	1001	0.18	0.14	0.16	87	−6.10	0.78	0.044	< 0.01
Class C									
0.0–0.3	838	1.45	1.15	1.12	77	−3.95	0.79	0.050	< 0.01
0.3–0.6	822	0.53	0.39	0.61	114	−5.08	0.84	0.029	0.087
0.6–0.9	780	0.28	0.22	0.27	96	−5.67	0.83	0.037	0.010
0.9–1.2	672	0.20	0.15	0.21	104	−6.03	0.88	0.060	< 0.01
Class D									
0.0–0.3	638	1.34	1.15	0.87	66	−4.01	0.73	0.051	< 0.01
0.3–0.6	617	0.65	0.53	0.52	80	−4.79	0.78	0.052	< 0.01
0.6–0.9	558	0.41	0.32	0.34	84	−5.29	0.82	0.048	< 0.01
0.9–1.2	493	0.29	0.22	0.31	105	−5.65	0.86	0.056	< 0.01

s.d. = standard deviation; C_{var} = coefficient of variation.
[a] Johnson s_B transformation is used for all cases in this table.
[b] Kolmogorov test statistic.
[c] Probability of obtaining a more extreme value of D.

Randomized parameters

In the generation of the 2000 parameter sets, randomized parameters were soil hydraulic group, weather year, pesticide degradation rate, and values of field capacity, wilting point, and organic matter for each stratum. All randomization was performed using routines from the International Mathematical and Statistical Libraries (1981).

Selection of soil hydraulic groups was based on weighting of 5, 40, 30, and 25% for groups A, B, C, and D, respectively. This weighting represents the distribution of land area in Ohio as determined using the SIRS data base (Goran, 1983).

Weather data for each of the simulations were provided by randomly selecting one year of a 29-year record (1950–1978) available from Charles Mill Dam Weather station. The work of Gumbel (1958) indicates that 25–30 years are required to insure with 95% confidence that one year will be at least one standard deviation above the mean. During this period, the total annual pre-

TABLE 5

Correlations among transformed variables

Stratum (m)	OM + WP		FC + OM		FC + WP	
	N	Corr.	N	Corr.	N	Corr.
Class A						
0.0–0.3	118	0.738	52	0.624	51	0.757
0.3–0.6	119	0.630	49	0.404	49	0.759
0.6–0.9	111	0.487	42	0.427	42	0.811
0.9–1.2	98	0.456	38	0.170	39	0.761
Class B						
0.0–0.3	877	0.545	459	0.609	455	0.675
0.3–0.6	870	0.372	446	0.384	450	0.639
0.6–0.9	844	0.375	419	0.336	429	0.714
0.9–1.2	780	0.392	347	0.412	370	0.762
Class C						
0.0–0.3	673	0.495	369	0.577	370	0.745
0.3–0.6	664	0.473	355	0.409	361	0.775
0.6–0.9	627	0.457	321	0.434	334	0.784
0.9–1.2	543	0.434	264	0.456	289	0.751
Class D						
0.0–0.3	488	0.538	228	0.496	226	0.847
0.3–0.6	472	0.434	201	0.454	204	0.845
0.6–0.9	420	0.456	171	0.369	174	0.782
0.91.2	384	0.415	137	0.106	145	0.687

OM = organic matter; WP = wilting point; FC = field capacity; N = sample size; Corr. = correlation.

cipitation ranged from 0.47 to 1.1 m with a mean of 0.82 m and a standard deviation of 0.13 m.

The degradation rate of aldicarb residues was randomized using a triangular distribution ranging from 0.023 to 0.012 day^{-1} with a mean of 0.015. These rates were based on an analysis of field data reported by Jones (1986). In the Ohio region, degradation rates appear not to vary significantly with depth (Jones, 1986).

The values of the transformed variables of field capacity, wilting point, and organic matter for each stratum were selected using a multivariate normal distribution. Inverse transformations were then used to obtain the actual values. In the cases where movement of aldicarb residues past 1.5 and 3.0 m was predicted, the properties selected for the 0.9–1.2 m stratum were used for the soil below 1.2 m.

Aldicarb sorption partition coefficients were calculated given the soil organic matter content using an organic-carbon-based sorption partition coefficient (K_{oc}) of 20 for aldicarb (Hornsby et al., 1983). For aldicarb, K_{oc} values up to 40 (Briggs, 1981) have been reported. The sorption coefficients for aldicarb

sulfoxide and aldicarb sulfone are considerably lower PRZM predicted movement using a K_{oc} of 31.6 was generally greater than observed in a wide range of field experiments (Jones et al., 1986). Therefore, the use of the K_{oc} value of 20 is conservative.

Fixed variables

Several variables required by PRZM were not varied from simulation to simulation, and the fixed values for these variables are summarized in Table 6. SCS curve numbers are based on information from Baker (1983, 1985).

Corn is planted in Ohio between April 20 and May 30 (Burkhead et al., 1972). Potentially the planting date may impact pesticide movement due to timing of seasonal rainfall; however, sensitivity tests indicated no significant differences within the planting window. Crop parameters associated with May 5, the most common planting date (Eurkland et al., 1972), were, therefore, incorporated into the simulations. Aldicarb applications to corn are made at planting; an application rate of 1.68 kg ha^{-1} incorporated in the upper 0.05 m of soil was used in the simulations.

In this study, losses of aldicarb due to plant uptake and erosion were conservatively set to zero since the total of both these losses will generally be less than 10 percent of the applied material (Dejonckhere et al., 1983). Losses due to volatilization of aldicarb residues are not significant (Supak et al., 1977).

RESULTS AND DISCUSSION

The 90th, 95th, and 99th percentiles of the amount of aldicarb residues moving past depths of 0.3, 0.6, 0.9, and 1.5 m were calculated as a function of

TABLE 6

Values of fixed parameters

Soil bulk density	Median value, Table 1
SCS curve numbers	
Hydrologic class	
A	77, 72, 75
B	86, 78, 82
C	91, 85, 88
D	94, 91, 93
Crop information	
Date of emergence	May 1
Date of maturity	July 25
Date of harvest	October 10
Root zone depth	0.9 m
Areal cropcover at full canopy	85%
Pesticide application	
Date	May 5
Rate	1.68 kg ha^{-1}

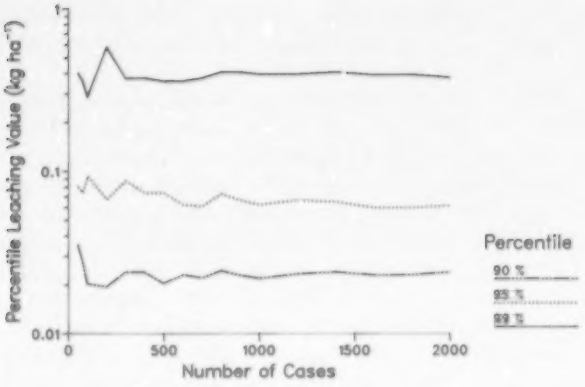

Fig. 1. Calculated percentile values for annual pesticide movement below 1.5 m for various sample sizes.

sample size (in increments of 50). Associated 95% confidence intervals were calculated using order statistics (Mosteller and Rourke, 1973). The percentile estimates and confidence interval widths for the amount of movement below 1.5 m are presented in Figs. 1 and 2. Generally, as the sample size approached 500 the percentile estimates converged for all depths. The width of the associated confidence intervals decreased, of course, as the sample size increased.

The number of samples required for convergence appears to be consistent with previous results. Persaud et al. (1985) determined that a sample size of 200 was adequate to describe noninteracting, steady state solute movement in

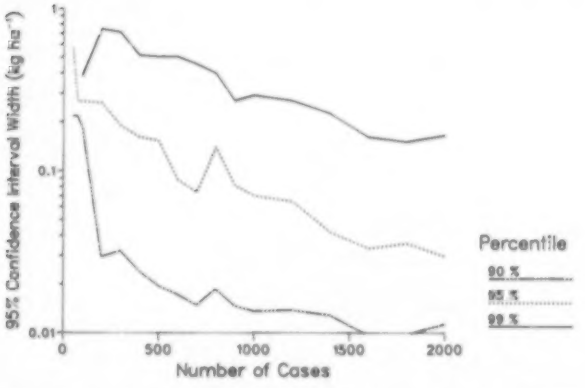

Fig. 2. Calculated 95% confidence interval widths for pesticide movement below 1.5 m for various sample sizes.

heterogeneous soil affected by hydrodynamic dispersion and pore water velocity (two variables). In our study, 16 randomized variables were used to evaluate transient movement of an interacting solute.

The half-width of confidence intervals is sometimes used to provide a measure of the uncertainty of interval estimates. As such, a relative uncertainty value was constructed by dividing the half-width of the 95% confidence interval for a given percentile by the value of the percentile estimate itself. For example, the 99th percentile after 2000 cases for movement past 1.5 is approximately 0.4 kg ha^{-1} and the confidence interval half-width is approximately 0.1 kg ha^{-1}. So, the relative uncertainty value associated with this estimate is 25%.

The relative uncertainty values for the 90th, 95th, and 99th percentiles are shown in Fig. 3 as a function of sample size. The fluctuation is greatest for small sample sizes and highest percentiles. For the relative uncertainty to decrease to significantly lower levels, substantially more simulations are required.

The predicted amounts of aldicarb residue movement in the 2000 simulations were used to construct a cumulative probability distribution (Fig. 4). In about 97% of the simulations, the model predicted residue movement less than 0.1 kg ha^{-1} below 1.5 m, and in about 99% of the simulations movement was less than 0.1 kg ha^{-1} below 3.0 m. Conversely, the model predicts residue movement exceeding 0.1 kg ha^{-1} below 1.5 m in about three percent of the simulations and below 3.0 m in about one percent of the simulations.

Groundwater concentrations from these fluxes are dependent on the saturated zone degradation rate, distribution of rainfall, aquifer porosity, and residue plume thickness. For example, 0.1 kg ha^{-1} aldicarb residue movement into groundwater at one time will typically result in a calculated groundwater concentration of 10 to 25 μg l^{-1} (porosities of 0.2–0.4 and residue plume thicknesses of 1–3 m). Actual groundwater concentrations may be somewhat less due to conservative predictions of residue movement by PRZM.

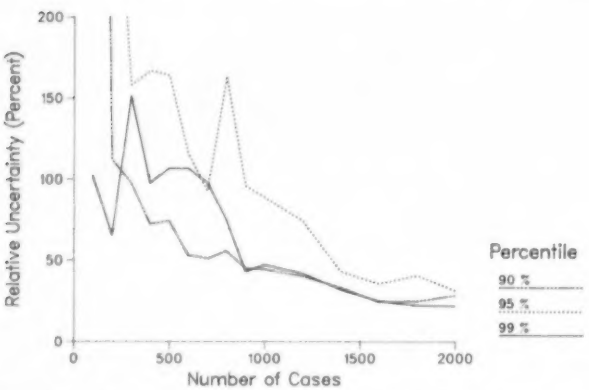

Fig. 3. Relative uncertainty of PRZM-simulated annual pesticide movement below 1.5 m for various sample sizes.

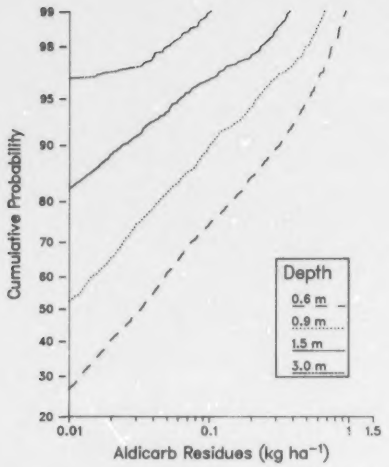

Fig. 4. Cumulative probability distribution for annual pesticide movement below selected depths for 2000 selected multivariate combinations.

Because the Monte-Carlo assessment procedure uses a national distribution for selected soil characteristics, the probabilities calculated with this procedure may sometimes underestimate or overestimate the leaching potential. For example, because yield of some crops (e.g., tobacco) on lighter-textured soils is poor, these crops are not usually grown on soils where leaching potential is highest. In this case, the assessment procedure may overestimate the probability of significant pesticide movement. Similarly, other crops cannot be grown on heavier-textured soils (e.g., peanuts) so the procedure may underestimate the occurrence of significant movement. For crops grown on a wide range of soils, the national distributions may not reflect actual regional distribution of soils used for agriculture. The use of a national distribution function facilitates a rapid screening procedure; however, the relevance to the region and crop must be evaluated.

Monte Carlo techniques can be used to predict pesticide movement and to estimate the uncertainty in the prediction; however, they provide little insight into cause and effect relationships. Therefore, predicted aldicarb movement was compared with simulation variables. Predicted aldicarb movement was most strongly related to field capacity. As shown in Fig. 5, the amount of aldicarb moving below 1.5 m exceeded 0.1 kg ha^{-1} in over 50% of the variable combinations for field capacities less than 0.07 m^3 m^{-3} (7 vol. %). These results indicate that any instances of aldicarb residues reaching groundwater beneath Ohio cornfields would usually occur in soils with field capacities less than about 0.1 m^3 m^{-3} and with water tables less than 3 m (Fig. 4).

To determine the extent and properties of low field capacity soils in Ohio, site-specific information was obtained from several sources (Goran, 1983;

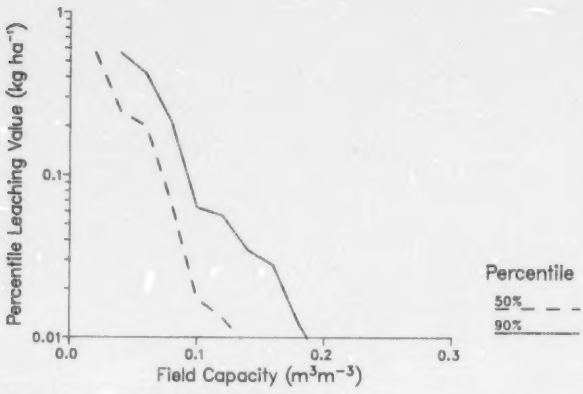

Fig. 5. Cause-effect relationship between field capacity and annual pesticide movement below 1.5 m.

Baker, 1983, 1985). Approximately one percent of the land in Ohio is classified as sands, loamy sands, and sandy loams. Soil series on which corn is grown include Oshtemo sandy loam, Spinks loamy sand, and Gillman loam. Generally, water tables are greater than 1.8 m deep. The soil most sensitive to pesticide movement was the Oshtemo sandy loam because of low values for organic matter and sub-surface field capacity (Table 7). Simulations were conducted using the Charles River Dam 29-year rainfall record. No residue movement exceeded 0.01 kg ha^{-1} below 1.8 m in any year.

The results of the Monte-Carlo simulation coupled with the additional site-specific simulations show that aldicarb residues would not be expected to appear in groundwater as a result of applications to corn in Ohio. For simulations that predict significant loadings to groundwater, additional evaluations would be required. These evaluations could include linking PRZM to a saturated zone model (e.g., Jones et al., 1986, 1987) to evaluate the magnitude and frequency of the pesticide residues and distances of migration from treated areas. Alternatively, a stochastic site-specific procedure including the saturated zone (e.g., Carsel et al., 1987) could be used. If these calculations

TABLE 7

Simulation parameters for Oshtemo sandy loam

Strata (m)	Field capacity ($m^3 m^{-3}$)	Wilting point ($m^3 m^{-3}$)	Organic matter (wt. %)
0.0–0.3	0.207	0.095	0.85
0.3–0.6	0.207	0.095	0.30
0.6–0.9	0.125	0.055	0.20
0.9–1.2	0.125	0.055	0.10
1.2–1.8	0.060	0.030	0.10

were to indicate levels of concern, appropriate field evaluations, monitoring and/or restrictions could be initiated. Management practices such as the timing of pesticide applications and restrictions to prevent applications near potable wells have been used in Florida and the northeastern United States.

CONCLUSIONS

The Monte-Carlo procedure coupled with additional site-specific simulations provides a relatively simple procedure for making regional assessments of pesticide leaching potential. The probability density functions for organic matter, field capacity, and wilting point may also have a variety of additional uses.

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